A DECADE OF OCEAN TESTING OF PRESSURE-RESISTANT CONCRETE STRUCTURES

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ABSTRACT

By means of long-term deep-ocean exposure and laboratory testing, experimental data have been obtained on compressive strength behavior, permeability, and durability of pressure-resistant concrete structural models (concrete spheres 66-inch O.D. by 4-1/8-inch wall thickness) subjected to continuously sustained hydrostatic pressure loading.

After 10-1/2 years of ocean exposure at water depths of 1,840 to 5,075 feet, the major findings include: (a) The implosion (failure) strength and stiffness of the concrete spheres and the uniaxial compressive strength of concrete specimens increased during the first 5-1/2 years exposure in the ocean and remained essentially constant during the next 5 years; (b) There has been no evidence of seawater permeating through the walls into the interior of ocean-exposed spheres externally coated with a waterproofing material; uncoated (bare concrete) spheres have a very low rate of water ingress, i.e., a permeability coefficient of about 10^{-14} ft/sec; and (c) Visual inspection and microstructure examination of retrieved specimens have not revealed any significant deterioration of the concrete matrix; no corrosion was visible on steel reinforcing bars which had as little as one inch clear cover.

This program has been a decade-long demonstration of the effective use of concrete in the ocean; it has been shown that concrete is a durable, reliable material for pressure-resistant structures for long-term deep-ocean applications.

INTRODUCTION

In September 1971 the Naval Civil Engineering Laboratory (NCEL) began an experimental program on the behavior of pressure-resistant concrete spherical structures placed in the deep ocean for long-term exposure. In situ inspections of the spheres were made annually by submersible over, to date, an 11-year period. At various times selected spheres and associated concrete and cement paste samples were retrieved from the ocean for laboratory testing.

This work was funded by the U.S. Navy's Deep Ocean Technology Program, and is a portion of the larger program of experimental studies begun at NCEL in 1967 on pressure resistant structures and structural components in various materials, primarily concrete in spherical and cylindrical configurations, and acrylic plastic for transparent spherical hulls and windows for internally and externally pressurized chambers.

The technical objectives of the ocean testing program were to obtain data on time-dependent failure, permeability, and durability of pressure-resistant concrete spherical structures subjected to sustained high pressure seawater for extended periods of time. Such data can contribute to a technology base from which engineering design guidelines may be prepared.

Another purpose of the program was to demonstrate the use of concrete hulls in real environmental conditions; thus, the findings will aid in establishing confidence in using concrete as a deep ocean construction material.

Information obtained earlier has been previously reported;^{1,2} this paper presents data obtained during the past 5 years and summarizes overall trends with primary emphasis on findings to date on concrete strength.

TEST DESCRIPTION¹

Eighteen hollow concrete spheres having a 66-in. outside diameter and a 4.12-in. wall thickness were placed in the ocean near Santa Cruz Island, Calif. (by free-falling from the surface) in water depths of 1,840 to 5,075 feet. When in place, each buoyant sphere floated about 20 feet off the seafloor to which it was anchored by the 2,600-lb weight of a 2-1/4-in. anchor chain 53 ft long (Figures 1 and 2).

Figure 1. Sphere assembly (simplified; after reference 1.).

Figure 2. Sphere No. 17 shown floating 20 ft above the seafloor after 8½ years in the ocean at a water depth of 2000 ft.

Each sphere was fabricated from 2 hemispheres, individually cast, bonded together at the equator. Control specimens from each batch of concrete consisted of standard 6-in.-diameter by 12-in.-long cylinders and an 18- by 18- by 14-in. block from which cores were subsequently drilled after exposure in the ocean or on land.

The concrete, commercially produced and delivered to the casting site in transit-mix trucks, was of consistently high quality with a nominal cement content of 7.8 sacks/yd³, water/cement ratio of 0.40, and 28-day compressive strength of 7,900 psi.

Sixteen spheres were unreinforced concrete. Eight of these were coated on the exterior with a waterproofing agent and eight left uncoated (i.e., bare concrete). Two spheres were lightly reinforced with 0.5 in. diameter deformed steel bars with concrete cover varying from 1 to 2.5 in. Half the exterior of each of these 2 spheres was waterproofed. The purpose of the steel was not to strengthen the spheres but rather to determine whether corrosion problems would occur in the high pressure, chemically active seawater environment which, however, is fairly cold (41°F) with a very low dissolved oxygen content (< 1 ml/l).

The ocean depth range for the spheres corresponds to predicted relative load levels of from 0.36 to 0.83 where the relative load level, P_s/P_{im}^P , is defined as the ratio of the sustained pressure to the predicted short-term implosion pressure. The nominal design depth for the spheres was 3,000 ft. Thus, time-dependent failure was anticipated for some of the spheres subjected to the higher load levels.

Permeability data were obtained by two methods: by measuring the water found inside the recovered spheres, and by counting the number of chain links between the spheres and the seafloor during periodic in situ inspection by submersible. Each sphere, which was about 950 lb buoyant, supported about 30 links of its anchor chain off the seafloor. As seawater was absorbed by and permeated through the concrete, the sphere weight increased, buoyancy decreased, and less chain was supported. Thus, the decrease of one chain link between the sphere and the seafloor indicated about one-half ft³ of seawater had been taken on by the sphere.

RESULTS

Concrete Strength

One of the 18- by 18- by 14-in. blocks for each sphere was placed in the ocean with the sphere, one block was stored outdoors on land, and a number of the 6 by 12-in.-long cylinders were continuously fog cured in a moist room at 100% relative humidity and 73°F.

Ocean-exposed concrete blocks were retrieved from the ocean on three occasions: 1 block after 1 year in the ocean, 4 blocks after 5.3 years, and 2 after 10.5 years. Each recovered block and its on-land field-exposed companion were cored to produce 4 cylinders nominally 6-in. diameter by 12-in. long. The cored cylinders and companion continuously fog-room cured cast 6 by 12 cylinders were tested for compressive strength, modulus of elasticity and Poisson's ratio. Drilled cores are known to be, in general, weaker in compressive strength than cast cylinders of the same concrete.³ For the following strength comparisons the core strengths are adjusted by increasing the measured core strength by 7% as discussed in Reference 2.

The results are summarized in Figure 3 which shows the relative strengths of the concrete in the three environments at total ages of 1.3, 5.6 and 10.8 years. The relative strength is the compressive strength of the concrete at a given age compared to the compressive strength at 28 days of fog-cured specimens.

Figure 3. Effect of long-term exposure environment on relative compressive strength. Strength of cores has been adjusted to represent that of cast cylinders. (Data for 1.3 and 5.6 years from Reference 2.).

The continuously fog cured specimens increased in strength by 23% at 1.3 years, to 35% above the baseline strength at 5.6 years of age, and were still at 35% at 10.8 years.

This pattern of rapid strength gain at early ages and then slowing down and even plateauing at later ages is typical of concrete.

The on-land field-exposed concrete, tested in the air-dried condition, shows a similar but smaller gain to 5.6 years, as expected, but indicates a loss of strength during the second 5 year period. This drop was not expected, but it may be noted that the outdoor conditions, especially relative humidity and temperature, varied considerably on a daily as well as seasonal basis in contrast to the fog room and the in-ocean conditions which were constant throughout the exposure to these environments.

The most interesting findings are, of course, those of the ocean-exposed concrete. This concrete showed a decrease in strength on first being placed in the ocean. This decrease is considered to be due to the concrete changing from an air-dry condition at time of deployment (after its initial 28-day cure it

had been stored outdoors for several months until deployment) to a saturated condition in the ocean. It is well known that the uniaxial compressive strength of wet (saturated) concrete is 10% or more lower than otherwise comparable dry concrete. However, after the initial loss in strength the concrete continued to cure in the ocean and gain strength. At 1.3 years age it's strength was still 3% less than the reference concrete, but by 5.6 years total age it was 15% above the baseline strength, and was still at that strength level at 10.8 years age. Thus, the ocean exposed concrete, after an initial loss, gained strength and then leveled off at the later age, much the same as the reference fog-cured concrete, but at a lower attained strength.

Short-Term Strength of Spheres

Three of the spheres, numbers 11, 12 and 13, were retrieved from ocean depths of 3,140, 2,790, and 2,635 ft, respectively, after 5.3 years in the ocean and tested to implosion failure by applying external pressure in NCEL's 72-in.-diameter pressure vessel. Two more spheres, numbers 10 and 18, were recovered from 3,200 and 1,840 feet, respectively, and tested after 10.5 years exposure.

Figure 4 shows the load-deformation curves for spheres numbers 10 and 18. Each sphere was placed in the pressure vessel and surrounded by seawater in which the pressure was then steadily increased at 50 psi/min until failure. Also each sphere was filled on the inside with seawater which, however, was vented (though a penetration in the pressure vessel head) to atmospheric pressure. Thus, as the external pressure was increased on the sphere it became smaller and forced out some of its internal water, which was measured. This provided a direct measure of the decrease in internal volume of the sphere, and by calculation, the average bi-axial hoop strain in the sphere wall. The average bi-axial wall stress is

Figure 4. Short-term load/deformation behavior of concrete spheres preloaded 10.5 years.

directly calculated from the geometric ratio of the cross-sectional area of the 4.12-in.-thick sphere wall to the total 66-in.-diameter sphere cross-sectional area ("thin-wall sphere" assumption). The concrete of sphere #10 (which was uncoated and had, when recovered, 1.9 ft³ of water on the inside) was assumed to be saturated. The lower half of sphere #18 was also uncoated and saturated; failure occurred in this saturated lower hemisphere.

The respective implosion (failure) loadings were very close together at 2,720 and 2,760 psi. Note that the load-deflection curves are quite smooth to the point of failure; they are fairly close together but sphere #18 is a little stiffer with a calculated secant modulus of elasticity at 50% of failure of 5.7×10^6 psi compared to 5.0×10^6 psi for sphere 10. The small amount of reinforcing steel in sphere #18 had little effect on the behavior of the sphere.

Failure was primarily in the compression-shear mode although there was also in-wall delamination-type cracking "parallel to" (concentric to) and about 1 inch below the external surface, which led to exfoliation of large (e.g., 1 foot across) fragments of very constant thickness (Figures 5 and 6). Failure surfaces passed through (not around) coarse aggregate particles.

Figure 5. Sphere No. 10 after implosion under short-term loading (in a pressure vessel) to 2720 psi max external pressure.

Figure 6. Details of failure mode of concrete sphere No. 10 after short-term loading to implosion in a laboratory pressure vessel.

Figure 7 shows the load-deflection curves for all 5 spheres recovered from the ocean (after 5.6 or 10.5 years pre-loading at ocean pressures) and for three non-preloaded spheres tested to implosion under short-term (pressure vessel) loading at a younger age (0.5 year) under a previous test program.⁴

Figure 7. Summary of short-term load/deformation behavior of preloaded and non-preloaded concrete spheres. (Includes data from references 2 and 4).

This figure demonstrates several points. The short-term implosion failure strength of the "dry" (waterproofing coated) spheres are stronger, and deflect more before failure than do the saturated concrete spheres. This holds for the preloaded (ocean-exposed) spheres as a group, and for the non-preloaded spheres as a group.

Also the preloaded spheres are stronger and stiffer than the younger non-preloaded spheres. Both of these, of course, can be attributed to the in-ocean strength increase with age of the ocean spheres.

The short-term failure strength and the shape of the ocean-exposed sphere curves are not only close together at a given age, but are very similar for both 5.3 and 10.5 years, which corroborates the plateauing or maintaining of the uniaxial compressive strength during the second 5-year term.

Long-Term Loading

Of the original 18 spheres three have imploded in the ocean. Sphere #3 failed during its free-fall descent before it reached the seafloor at 4,330 ft during the original deployment. Sphere #1 at 5,075 ft depth and sphere #7 at 3,725 ft imploded in situ. They were first inspected at 3 years and 1.2 years, respectively, after deployment. Therefore, they are assumed to have failed either at initial touchdown or sometime during the period before the first inspection.

One sphere leaked and is lying on the seafloor intact (i.e., not imploded). One sphere has never been inspected. However, none of the other 13 spheres have imploded in the ocean. These spheres have continued to gain strength in place, and thus, it is assumed, have become less likely to fail.

Eight intact spheres remain floating in the ocean just above the seafloor in water depths ranging from 1,980 to 4,875 ft with relative load levels (the ratio of the sustained pressure, P_s , to the predicted failure load, P_{im}^P) of 0.3 to 0.7.

There are no current plans to retrieve more spheres. However, it is hoped that in situ inspections by submersible may be made from time to time in future years at least to observe whether the spheres continue to survive.

PERMEABILITY

Only brief comments will be made on permeability and durability.

Of the five spheres recovered from the ocean two were coated on the outside with the waterproofing material. After 5.3 years in the ocean neither of these contained any free water on the inside. The uncoated sphere recovered after 5.3 years contained 1.24 ft³ of water on the inside. The uncoated sphere #10 and the half-coated sphere #18 retrieved after 10.5 years submergence contained 1.91 and 0.37 ft³ of permeated water respectively. Thus, the plain uncoated concrete was not "perfectly watertight", but these represent very small quantities of water. In sphere #10 the water that has permeated the 4-1/8-in.-thick concrete in over a 10.5 years time at a pressure head of 1,420 psi represents about 3% of the interior volume of the sphere.

Darcy's theory assumes that the coefficient of permeability is constant with time, which is probably not the case for permeation of water into the spheres. However, if an average permeation rate is assumed, then the permeability coefficients calculated for the 3 water-containing spheres (with differing pressure heads, time in ocean and overall area) are reasonably consistent with each other, ranging from 0.6×10^{-14} to 1.2×10^{-14} ft/sec, and with the expected permeability of mature, well-consolidated concrete with a water/cement ratio of 0.4.

DURABILITY

There was no visible deterioration of the concrete matrix of the spheres and blocks retrieved from the ocean after 10.5 years exposure.

Also, no corrosion was visible on the steel reinforcing bars which had as little as 1 inch of clear cover over the steel, and in the uncoated lower hemisphere the concrete was saturated with seawater for a number of years (Figure 8).

Figure 8. Detail of wall of sphere No. 18 showing one-half inch diam reinforcing steel bar with no visible corrosion after 10 1/2 years in the ocean at a water depth of 1830 ft.

CONCLUSION

This program has been a decade-long demonstration of actual concrete model structures in the ocean; concrete has been demonstrated to be a durable, reliable material for pressure-resistant structures for long-term deep-ocean applications.

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